COSMIC RAYS FROM TRANS-RELATIVISTIC SUPERNOVAE

RAN BUDNIK[1], BOAZ KATZ[1], ANDREW MACFADYEN[2,3] AND ELI WAXMAN[1]

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ABSTRACT

We derive constraints that must be satisfied by the sources of $\sim 10^{15}$ to $\sim 10^{18}$ eV cosmic rays, under the assumption that the sources are Galactic. We show that while these constraints are not satisfied by ordinary supernovae (SNe), which are believed to be the sources of $\lesssim 10^{15}$ eV cosmic rays, they may be satisfied by the recently discovered class of trans-relativistic supernovae (TRSNe), which were observed in association with gamma-ray bursts. We define TRSNe as SNe that deposit a large fraction, $f_R > 10^{-2}$, of their kinetic energy in mildly relativistic, $\gamma\beta > 1$, ejecta. The high velocity ejecta enable particle acceleration to $\sim 10^{18}$ eV, and the large value of f_R (compared to $f_R \sim 10^{-7}$ for ordinary SNe) ensures that if TRSNe produce the observed $\sim 10^{18}$ eV cosmic ray flux, they do not overproduce the flux at lower energies. This, combined with the estimated rate and energy production of TRSNe, imply that Galactic TRSNe may be the sources of cosmic rays with energies up to $\sim 10^{18}$ eV.

Subject headings: acceleration of particles — cosmic rays — gamma-rays: bursts — supernovae: general — supernova remnants

1. INTRODUCTION

The spectrum of cosmic rays (CRs) extends from $\sim 10^9$ eV to $\sim 10^{20}$ eV (see Blandford & Eichler 1987; Axford 1994; Nagano & Watson 2000, for reviews). While there is a wide consensus that the sources of CRs of energy $\lesssim 10^{15}$ eV are Galactic supernovae (SNe), and that the sources of CRs above 10^{19} eV are extra-Galactic (possibly GRBs or AGN, e.g. Waxman 2004c, for a recent review), there is no consensus regarding the sources of cosmic rays in the energy range of $\sim 10^{15}$ eV to $\sim 10^{18}$ eV.

The CR spectrum steepens at $\sim 10^{15}$ eV, the "knee," and then extends smoothly to $\sim 10^{18}$ eV. These characteristics disfavor a transition from Galactic to extra-Galactic sources in this energy range, since for such a transition one would naturally expect either a flattening of the spectrum or a marked drop of the flux at the transition energy. In fact, these characteristics suggest that the same type of sources, or the same class of sources, produces the CRs over the entire energy range of $\sim 10^9$ eV to $\sim 10^{18}$ eV. Indeed, it has been suggested that Galactic SNe are the sources of all CRs in this energy range (e.g. Bell & Lucek 2001).

Over the past several years a new type of supernova explosions has been discovered, to which we will refer as "trans-relativistic supernovae" (TRSNe). We define TRSNe as supernovae which, unlike ordinary SNe, deposit a significant fraction, $f_R > 10^{-2}$, of their kinetic energy in mildly relativistic, $\gamma\beta > 1$, ejecta (the corresponding fraction for ordinary SNe is typically $\leq 10^{-7}$; see § 3.2 for a detailed discussion). Such TRSNe have been discovered recently in association with gamma-ray bursts (GRBs). Hereafter we will use the term SNe for ordinary supernovae, which deposit only a small fraction of their kinetic energy in relativistic ejecta, and the term TRSNe for supernova explosions with $f_R > 10^{-2}$.

Various terms have been used in the literature to describe supernovae associated with GRBs: GRB-SNe, "hypernovae", broad-line type Ic SNe, and others. We have chosen here to use the term "trans-relativistic supernovae" for several rea-

sons. First, it captures the main physical property that characterizes supernovae that may produce the observed $\sim 10^{15}$ eV to $\sim 10^{18}$ eV cosmic-ray flux, namely $f_R > 10^{-2}$. Second, supernovae associated with GRBs may not all be similar to each other. SN2006aj, for example, is qualitatively different from the other GRB associated supernovae. Although there is evidence for this explosion to be characterized by $f_R > 10^{-2}$, its total kinetic energy is similar to that of ordinary SNe, $\sim 10^{51}$ erg, while the other GRB associated supernovae appear to be ten times more energetic. Thus, while SN2006aj does not fit into the "hypernovae" (i.e. highly energetic) category, it does fit into the TRSNe category and should be considered as a potential source of $\sim 10^{15}$ eV to $\sim 10^{18}$ eV cosmic-rays. Finally, it should be kept in mind that not all TRSNe are necessarily associated with GRBs.

We show in this letter that Galactic TRSNe may be the sources of $\sim 10^{15}$ eV to $\sim 10^{18}$ eV CRs. We first derive in § 2 constraints, which apply to both SNe and TRSNe, that must be satisfied by Galactic sources of $\sim 10^{15}$ eV to $\sim 10^{18}$ eV. We then show in § 3 that while these constraints are not satisfied by SNe, they may be satisfied by TRSNe. Our results are summarized and their implications are discussed in § 4.

2. CONSTRAINTS ON GALACTIC SOURCES OF CRS

We consider three constraints which must be satisfied by the candidate sources of CRs at high energy, $\varepsilon \sim 10^{18}$ eV. First we consider in § 2.1 constraints on the rate of occurrence of the sources in the Galaxy and on their energetics. The constraints derived in § 2.1 are applicable to any (Galactic) candidate source. Next, we consider in § 2.2 and § 2.3 constraints that are applicable to SNe and TRSNe. These sources are expected to accelerate particles to high energies through the collisionless shocks which they drive into the plasma surrounding the exploding star. In § 2.2 we derive constraints on the velocity of the shell ejected by the explosion, and in § 2.3 we derive constraints on the structure of the ejecta.

2.1. *Rates and energetics*

In order for a certain type of sources to be the main contributor to the observed CR flux at some energy ε_0, the sources must satisfy the following conditions:

[1] Physics Faculty, Weizmann Institute, Rehovot 76100, Israel
[2] Institute for Advanced Study, Princeton, NJ 08540, USA
[3] Physics Department, New York University, NY, NY 10003, USA

1. The energy production rate at ε_0 should be sufficient to explain the observed flux, and

2. The Galactic event rate, that is the rate of occurrence of the sources in the Galaxy, should not be much lower than one event per Galactic confinement time of CRs with energy ε_0.

Consider a source with a Galactic occurrence rate of $\dot{N}_s$ and an energy per event of E_s. E_s denotes the energy available for the acceleration of 10^{18} eV CRs, rather than the total energy released. In SN explosions, for example, the energy available for CR acceleration is the energy deposited in the shock wave driven by the ejecta. Since the maximum energy to which particles may be accelerated increases with shock velocity (see § 2.2), the energy available for acceleration of particles to 10^{18} eV is the energy carried by the fastest (outermost) part of the ejecta, which drives, at early times, a sufficiently fast shock. This energy may be significantly smaller than the total kinetic energy of the (slower) ejecta. We assume that the source produces an energy spectrum of accelerated particles given by

$$\varepsilon^2 \frac{dN}{d\varepsilon} = \zeta_s(\varepsilon) E_s. \tag{1}$$

Here $\zeta_s(\varepsilon)$ is the fraction of E_s that is deposited in CRs within a logarithmic energy interval around ε. The resulting energy density of CRs per unit logarithmic particle energy is

$$\varepsilon^2 n(\varepsilon) = \frac{\zeta_s(\varepsilon) \dot{N}_s \tau_c(\varepsilon) E_s}{V_G}, \tag{2}$$

where $n(\varepsilon)$ is the number density per unit CR energy, τ_c is the confinement time of the particles in the Galaxy, and V_G is the effective volume of the Galaxy in which the particles are confined. We assume that this effective volume is energy independent.

To reduce uncertainties we compare the resulting densities with those of low energy, 10^9 eV, CRs, assuming that in this energy range the CRs are accelerated predominantly by SNe. Using Eq. (2), the ratio of CR number densities (per unit CR energy) at low and high energy, $n_{l,h} = n(\varepsilon = \varepsilon_{l,h})$, is

$$\frac{\varepsilon_h^2 n_h}{\varepsilon_l^2 n_l} \approx \frac{\dot{N}_s}{\dot{N}_{SN}} \frac{\tau_c(\varepsilon_h)}{\tau_c(\varepsilon_l)} \frac{E_s}{E_{SN}} \frac{\zeta_s(\varepsilon_h)}{\zeta_{SN}(\varepsilon_l)}, \tag{3}$$

where E_{SN} is the characteristic kinetic energy of a SN explosion. For $\varepsilon_h = 10^{18}$ eV and $\varepsilon_l = 10^9$ eV the observed ratio is (e.g. Nagano & Watson 2000, and references within)

$$\frac{\varepsilon_h^2 n_h}{\varepsilon_l^2 n_l} \approx (10^{15}/10^9)^{-0.7}(10^{18}/10^{15})^{-1.0} \simeq 10^{-7}. \tag{4}$$

Using Eqs. (3) and (4), we find that the sources of CRs at $\varepsilon = \varepsilon_h = 10^{18}$ eV must satisfy

$$\frac{N_s}{N_{SN}} \approx 10^{-7} \zeta^{-1} \left(\frac{E_s}{E_{SN}} \right)^{-1}, \tag{5}$$

where $N_s = \dot{N}_s \tau_c(\varepsilon_h)$ and $N_{SN} = \dot{N}_{SN} \tau_c(\varepsilon_l)$ are the average numbers of events that contribute to the observed flux at any given time at energies $\varepsilon_h = 10^{18}$ eV and $\varepsilon_l = 10^9$ eV respectively, and $\zeta \equiv \zeta_s(10^{18}$ eV$)/\zeta_{SN}(10^9$ eV$)$. Using the confinement time of 1 GeV protons in the Galaxy, $t_c(10^9$ eV$) \approx 10^{7.5}$ yr (Webber & Soutoul 1998; Yanasak et al. 2001), Eq. (5) may be written as

$$N_s \approx 0.03 \zeta^{-1} \left(\frac{E_s}{E_{SN}} \right)^{-1} \dot{N}_{SN,-2}, \tag{6}$$

where $\dot{N}_{SN} = 0.01 \dot{N}_{SN,-2}$ yr^{-1}. The requirement that the event rate should exceed one event per Galactic confinement time, $N_s \gtrsim 1$, implies

$$\zeta \frac{E_s}{E_{SN}} < 0.03 \dot{N}_{SN,-2}. \tag{7}$$

The confinement time of CRs of energy $\sim 10^{18}$ eV is likely to be significantly larger than the light crossing time of the Galaxy, $\sim 10^4$ yr, due to the following argument. The observed energy evolution of the depth of maximum, X_{max}, of extreme air showers suggest that composition of CRs at $\sim 10^{18}$ eV is dominated by nuclei with moderate atomic number Z (Gaisser et al. 1993; Nagano & Watson 2000). Consider therefore the Larmor radius of a CR particle with atomic number $Z = 10 Z_1$ and an energy $\varepsilon = 10^{18} \varepsilon_{18}$ eV,

$$R_L \approx 40 B_{-5.5}^{-1} \varepsilon_{18} Z_1^{-1} \text{ pc},$$

where $B = 3 B_{-5.5} \mu G$ is the Galactic magnetic field. Since the Larmor radius of such particles is much smaller than the thickness of the CR disk, ~ 1 kpc, the propagation of $\varepsilon = 10^{18}$ eV CRs is expected to be strongly affected by the Galactic magnetic field. The transition to non confined particles, for which the confinement time is comparable to the light crossing time, should then occur at $\gtrsim 10^{19} Z_1$ eV. Using therefore $\tau_c(10^{18}$ eV$) = \tau_{4.5} 10^{4.5}$ yr, Eqs. (3) and (4) give

$$\frac{\dot{N}_s}{\dot{N}_{SN}} = 10^{-4} \tau_{4.5}^{-1} \left(\frac{E_s}{E_{SN}} \right)^{-1} \zeta^{-1}. \tag{8}$$

The constraint that the Galactic event rate be larger than one event per confinement time can be written as:

$$\frac{\dot{N}_s}{\dot{N}_{SN}} > 3 \times 10^{-3} \tau_{4.5}^{-1} \dot{N}_{SN,-2}^{-1}. \tag{9}$$

Eqs. (7), (8) and (9) (any one of these can be derived from the other two) describe the constraints on the occurrence rate and energetics of the sources of $\sim 10^{18}$ eV CRs.

A note is in order regarding the value of the parameter $\zeta \equiv \zeta_s(10^{18}$ eV$)/\zeta_{SN}(10^9)$ eV. In the following, we consider sources that accelerate particles through collisionless shocks in the surrounding medium driven by fast ejecta. Note that although a complete theory, based on first principles, of particle acceleration in collisionless shocks is not available, there are strong theoretical arguments and observational evidence indicating that for both non-relativistic and relativistic shocks a considerable fraction of the post shock energy can be converted to relativistic particles with a spectrum that follows $\varepsilon^2 dN/d\varepsilon \approx \varepsilon^0$ (see, e.g. Blandford & Eichler 1987; Axford 1994; Waxman 2006, for reviews). If both SNe and the sources of 10^{18} eV CRs deposit a significant fraction of their energy in accelerated particles with a spectrum $dN/d\varepsilon \propto \varepsilon^{-2}$, the value of ζ would be of order unity.

2.2. Maximum energy

We assume that the particles are accelerated in the vicinity of a collisionless shock wave with (a time dependent) velocity $v_S = \beta_S c$ that is driven into the surrounding medium by an ejecta of mass M_{ej}, initial velocity $v_{ej} = \beta_{ej} c$ and kinetic energy $E_{ej} = (\gamma_{ej} - 1) M_{ej} c^2$. Here $\gamma_{ej} = (1 - \beta_{ej}^2)^{1/2}$ is the ejecta's Lorenz factor. We consider two options for the density distribution of the surrounding medium: A homogeneous interstellar medium (ISM) or a progenitor wind with a density profile $\rho \propto r^{-2}$.

At any given time, the maximum energy to which particles can be accelerated is given by

$$\varepsilon_{\max} \sim Ze\beta_S B_d r_S \qquad (10)$$

(e.g. Waxman 2004c, for a recent review). Here, r_S is the radius of the shock and B_d is the minimum of the magnetic field in the pre-shock (upstream) and post-shock (downstream) plasma, measured in downstream frame. We should stress that the energy given by Eq. (10) is an upper limit, and that the maximum energies attained are likely to be lower. For example, if particles are accelerated via Fermi's diffusive shock acceleration, the maximal energy would be a few times lower for Bohm limit diffusion, and much lower for slower diffusion.

There is growing evidence that the magnetic field in the vicinity of non-relativistic collisionless shocks in SNRs and gamma-ray bursts (GRBs) afterglows is amplified to values greatly exceeding the ambient magnetic field both in the upstream and downstream. In the past few years, high resolution X-ray observations have provided indirect evidence for magnetic fields of values as high as $100\,\mu$G in the ($v_S \sim$ few $\times$ 1000 km s^{-1}) shocks of young SNRs (see Bamba et al. 2003; Vink & Laming 2003; Völk et al. 2005). For relativistic shocks in the afterglow phase of GRBs, a very large magnetic field in the downstream is inferred from measurements (see Waxman 2006, for review), that can not be explained as a mere compression of the ambient field and requires a fair fraction of the kinetic energy of the shock to be transformed into magnetic energy. Li & Waxman (2006) have furthermore shown that in GRB afterglow shocks strong amplifications of the magnetic field in the upstream can be also inferred. We therefore assume that the magnetic field is amplified by the shock both in the upstream and in the downstream to values close to equipartition

$$B_d = \sqrt{\epsilon_B 8\pi\rho v_S^2 \gamma_S^2}. \qquad (11)$$

Initially, the shock and ejecta velocities (which are similar) are constant with time while the radius increases linearly. For the density distributions considered here the maximal acceleration energy is attained when the ejecta begins to decelerate. This happens roughly when the energy in the swept up material is comparable to the initial ejecta energy, i.e. when $M_{\text{swept}} \sim M_{\text{ej}}/\gamma_{\text{ej}}$. In case the shock is propagating into a homogeneous ISM, the deceleration radius is given by

$$r_{\text{hom}} \approx \left(\frac{M_{\text{ej}}}{\frac{4\pi}{3} n_0 m_p \gamma_{\text{ej}}} \right)^{1/3}, \qquad (12)$$

where n_0 is the ISM particle density per cm^3. Using Eqs. (10), (11) and (12), the maximum energy of an accelerated particle is

$$\varepsilon < 3 \times 10^{17} Z_1 \epsilon_{B,-1}^{1/2} \left(\frac{M_{\text{ej}}}{10 M_\odot} \right)^{1/3} n_0^{1/6} \beta_{\text{ej},-2}^2 \gamma_{\text{ej}}^{2/3} \text{eV}. \qquad (13)$$

Here $\epsilon_B = 0.1\epsilon_{B,-1}$ and $\beta_{\text{ej}} = 10^{-2}\beta_{\text{ej},-2}$.

For a shock propagating into a progenitor wind with a density profile $\rho = \dot{M}/4\pi r^2 v_w$, where $\dot{M}$ is the mass loss rate and v_w is the wind velocity, the deceleration radius is

$$r_{\text{wind}} \approx \frac{M_{\text{ej}} v_w}{\gamma_{\text{ej}} \dot{M}}. \qquad (14)$$

Using Eqs. (10), (11) and (14), the maximum energy of an accelerated particle is

$$\varepsilon < 10^{16} Z_1 \epsilon_{B,-1}^{1/2} \left(\frac{\dot{M}_{-5}}{v_{w,8}} \right)^{1/2} \beta_{\text{ej},-2}^2 \gamma_{\text{ej}} \text{eV}. \qquad (15)$$

Here $\dot{M} = 10^{-5}\dot{M}_{-5}M_\odot/\text{yr}$ and $v_w = 10^8 v_{w,8}$cm/s. The maximum energy is independent in this case of the ejecta mass, i.e. of the deceleration radius, since for a $1/r^2$ density profile the maximum energy (for a fixed shock velocity) is independent of the shock radius.

Note, that this estimate is valid provided shock deceleration occurs while it is propagating within the $\rho \propto r^{-2}$ wind profile. The $\rho \propto r^{-2}$ dependence of wind density extends up to a radius where $\rho_w v_w^2 \approx P_{ISM}$, and the wind mass contained within this radius is

$$M_w \approx \frac{\dot{M}^{3/2}}{(4\pi v_w P_{ISM})^{1/2}} \approx 0.3 M_\odot \frac{\dot{M}_{-5}^{3/2}}{v_{w,8}^{1/2} P_{ISM,-0.5}^{1/2}}, \qquad (16)$$

where the ISM pressure is $P_{ISM} = 0.3\text{eV}/\text{cm}^3 P_{ISM,-0.5}$. The maximum energy is given by eq. (15) for $M_{\text{ej}}/\gamma_{\text{ej}} < M_w$, and it is lower otherwise.

2.3. Energy distribution within the ejecta

SN explosions produce non-uniform ejecta, with velocity rising towards the front edge of the ejecta. The shock driven by the fastest, outermost part of the ejecta is capable of accelerating particles to the highest energy. Here we consider the case where a small and fast part of the ejecta is responsible for accelerating cosmic rays to energies $\varepsilon_h \sim 10^{18}$ eV, and constrain the energy distribution of the slower parts of the ejecta by requiring that they do not produce a flux of lower energy CRs that exceeds the observed one.

We denote the amount of energy in ejecta moving faster than βc by $E_k(> \beta)$. Since we consider in this section a limited range of particle energies, we assume that each part of the ejecta contributes a constant fraction ζ_{ej} to each logarithmic bin of particle energies at $\varepsilon < \varepsilon_{\max}(\beta)$ (ignoring the possible energy dependence of ζ_{ej}). Under this assumption, the resulting energy flux per logarithmic particle energy interval is $\varepsilon^2 n(\varepsilon) \propto \tau_c(\varepsilon) E_k(> \beta(\varepsilon))$. Here $\beta(\varepsilon)$ ($\propto \varepsilon^{1/2}$ for $\beta \ll 1$) is the shock velocity required for accelerating up to ε, i.e. $\varepsilon_{\max}(\beta) = \varepsilon$.

Assuming that the part of the ejecta with velocities larger than some β_h is responsible for the CR spectrum at some ε_h, requiring the slower parts of the ejecta do not produce a flux of cosmic rays at lower energy that exceeds the observed flux implies

$$\frac{E_k(> \beta(\varepsilon))}{E_k(> \beta(\varepsilon_h))} < \frac{\varepsilon^2 n_{\text{obs}}(\varepsilon)}{\varepsilon_h^2 n_{\text{obs}}(\varepsilon_h)} \left[\frac{\tau_c(\varepsilon)}{\tau_c(\varepsilon_h)} \right]^{-1}, \qquad (17)$$

where n_{obs} stands for the observed CR number density (per unit CR energy). Since the measured energy flux per logarithmic particle energy interval in the range $10^{15}\text{eV} < \varepsilon < 10^{18}$ eV is roughly proportional to E^{-1}, and the confinement time is expected to decrease with energy, the energy distribution must satisfy

$$\frac{E_k(> \beta(\varepsilon))}{E_k(> \beta(\varepsilon_h))} < \left(\frac{\varepsilon}{\varepsilon_h} \right)^{-1}. \qquad (18)$$

3. APPLICATION TO SNE AND TRSNE

3.1. *SNe*

Eqs. (13) and (15) imply that typical SNe driven shocks, characterized by $\beta_{ej} \sim 10^{-2}$, are probably too slow to accelerate particles to 10^{18} eV, especially considering that these are optimistic upper limits. Another difficulty in attributing the production of 10^{18} eV CRs to ordinary SNe is related to the constraint of Eq. (8). According to this constraint, if SNe were capable of accelerating particles to energies as high as 10^{18} eV, the flux produced at these energies would exceed the observed flux by a large factor unless $\zeta \sim 10^{-4}$, i.e. unless the energy carried by 10^{18} eV CRs accelerated by the SN shock is smaller by a factor of 10^4 than that carried by 10^9 eV CRs accelerated by the same shock. Such a strong suppression is not expected for the case when the maximum acceleration energy exceeds 10^{18} eV, since in this case we expect equal energy to be deposited per logarithmic CR energy interval (see discussion at the end of section §2.1). For example, attributing this factor to an acceleration spectrum $dn/d\varepsilon \propto \varepsilon^{-p}$ with p different from 2, would require $p > 2.4$ which seems inconsistent with theory and SNR radio observations.

One may argue that the above problem may be circumvented by assuming that 10^{18} eV CRs are produced only by the fast, $\beta \gg 10^{-2}$, component of the SN ejecta, which carries only a small fraction of the total kinetic energy. This would lead, however, to violation of the constraint of Eq. (18). The typical energy distribution in SN ejecta is $E_k(>\beta) \propto \beta^{-5}$ for BSG progenitors and $E_k(>\beta) \propto \beta^{-6}$ for RSG progenitors (Matzner & McKee 1999). At non relativistic velocities $\varepsilon_{\max} \propto \beta^2$, implying $E_k(>\beta(\varepsilon)) \propto \varepsilon^{-5/2}$ or $E_k(>\beta(\varepsilon)) \propto \varepsilon^{-3}$ for BSGs and RGBs respectively. This is in clear contradiction with Eq. (18). That is, if one assumes that the fast part of the ejecta produces the observed 10^{18} eV CR flux, then the predicted flux at lower energies would far exceed the observed flux.

Bell & Lucek (2001) have argued that SN driven shocks are candidate sources of CRs above 10^{18} eV, based on an estimate of the maximum acceleration energy. They have considered a shock of velocity of $40,000 \text{km/s}$ driven into a massive wind, characterized by $\dot{M}_{-5} \sim 1$ and $v_{w,8} \sim 10^{-2}$, as inferred from radio observations of SN1993J. Indeed, for such parameters the SN driven shock may allow acceleration to $> 10^{18}$ eV, as indicated by Eq. (15). However, it should be realized that SN1993J is still young, and that the measured velocity therefore represents only the fast front edge of the ejecta, which contains only a small fraction of the ejecta mass and energy. This is well illustrated in the modeling of this SN by Woosley et al. (1994), where only a small fraction of the total mass and energy lies in such a high velocity component of the ejecta (see e.g. their fig. 6). As explained above, if the tail of the ejecta velocity distribution can account for the cosmic ray flux at some energy $\varepsilon_h \sim 10^{18}$ eV, then the steep profile of energy as a function of velocity would imply a CR flux at lower energies that far exceeds the observed flux.

3.2. *TRSNe*

During the past decade, four GRBs were observed to be associated with core collapse SNe of type Ic: GRB980425/SN1998bw (Galama et al. 1998), GRB030329/SN2003dh (Hjorth et al. 2003; Stanek et al. 2003), GRB031203/SN2003lw (Tagliaferri et al. 2004), and XRF060218/SN2006aj (Campana et al. 2006). All but GRB030329 were very faint, 4-5 orders of magnitude fainter than an average cosmological GRB. In all 4 cases there is evidence from radio observations for deposition of a significant part of the kinetic energy in a mildly relativistic part of the ejecta (Soderberg et al. 2006, and references therein). Although radio observations alone do not allow one to uniquely determine the energy carried by the relativistic ejecta (Waxman & Loeb 1999; Waxman 2004a), additional observational information enabled such a unique determination in two cases. For GRB980425/SN1998bw there is a robust estimate of the energy deposited in the fast, $\beta \geq 0.85$, part of the ejecta, based on long term radio and X-ray observations, which yield $E(\beta \geq 0.85) = 10^{49.7}$ erg (Waxman 2004b). Similar values are inferred for XRF060218/SN2006aj from prompt and afterglow X-ray observations (Waxman et al. 2007).

The SN light curves of SN1998bw, SN2003dh, and SN2003lw appear to be qualitatively similar, implying SN ejecta mass and energy of $E_{ej} \sim 5 \times 10^{52}$ erg, $M_{ej} \sim 10 M_{\odot}$ (e.g. table 6 of Mazzali et al. 2006a). Note, that the energy may be lower, $\sim 1 \times 10^{52}$ erg, if the explosion is not spherical, which is likely (Maeda et al. 2006). The SN light curve of SN2006aj is qualitatively different than the others, implying $E_{ej} \simeq 2 \times 10^{51}$ erg and $M_{ej} \simeq 2 M_{\odot}$ (in this case, the explosion is probably not highly non spherical; Mazzali et al. 2006b). The inferred E_{ej} and $E(\beta \geq 0.85)$ imply that a significant fraction of the kinetic energy is deposited in a fast, mildly relativistic part of the ejecta, $E(\beta \geq 0.85)/E_{ej} \geq 10^{-2}$.

Two points should be emphasized here. First, GRBs associated with TRSNe are different than cosmological GRBs: The amount of energy carried by relativistic ejecta in TRSN explosions, $\sim 10^{49.5}$ erg, is much lower than that of cosmological GRBs, which is $\sim 10^{51}$ erg, and the fastest part of the ejecta in a TRSN is only mildly relativistic, unlike the highly relativistic ejecta inferred from observations of GRBs. Second, the mechanism responsible for depositing $\sim 10^{49.5}$ erg in the mildly relativistic part of the ejecta is not understood. For the inferred values of $E_{ej}/M_{ej}c^2 \sim 10^{-3}$, the acceleration of the SN shock near the edge of the star is expected to deposit only $\sim 10^{-7} E_{ej}$ in the part of the ejecta expanding with $\gamma\beta > 1$ (Tan et al. 2001). This suggests that the mildly relativistic component is driven not (only) by the spherical SN shock propagating through the envelope, but possibly by a more relativistic component of the the explosion, e.g. a relativistic jet propagating through the star (Aloy et al. 2000; Zhang et al. 2003). For the present analysis, we use therefore only the observational constraints on the energy distribution within the ejecta.

With only 4 detected events, the TRSNe rate is rather uncertain. Estimates of the local ($z = 0$) rate range from $\sim 10^2$ to $\sim 10^3 \text{Gpc}^{-3} \text{yr}^{-1}$ (Guetta & Della Valle 2007; Soderberg et al. 2006; Liang et al. 2006; Pian et al. 2006). Comparing this to the local SN rate, $\approx 10^5 \text{Gpc}^{-3} \text{yr}^{-1}$ (e.g. Cappellaro et al. 1999), we find $\dot{N}_{\text{TRSN}}/\dot{N}_{\text{SN}} \approx 10^{-2.5 \pm 0.5}$. This estimate is consistent with the estimate of Podsiadlowski et al. (2004) of the rate of "hypernovae" in galaxies similar to the Milky Way. As mentioned in the introduction, the TRSNe rate may be higher if some TRSNe are not associated with GRBs (and hence were not identified following a GRB trigger). With these estimates at hand, we are now ready to determine whether or not TRSNe meet the constraints derived in § 2.

First, for $\beta \approx 0.8$ Eqs. (13) and (15) imply that the mildly relativistic part of TRSNe ejecta may indeed accelerate CRs up to energy exceeding 10^{18} eV. Second, for an energy

$E_r \sim 10^{49.5}$ erg in the relativistic part of the ejecta we have $E_s/E_{SN} \sim 10^{-1.5}$, satisfying the energetics constraint, Eq. (7), and $\dot{N}_{TRSN}/\dot{N}_{SN} \approx 10^{-2.5\pm0.5}$ satisfying the rate constraint, Eq. (8). Note, that for TRSNe we expect $\zeta \sim 1$, based on their radio and X-ray observations. These observations imply that the collisionless shocks driven by the mildly relativistic ejecta into the wind surrounding the progenitor transfer a significant fraction of the energy to a population of shock accelerated electrons, and that the accelerated electron spectrum follows $\varepsilon^2 dN/d\varepsilon \approx \varepsilon^0$ over a wide range of energies, from electrons emitting synchrotron radiation in the radio band over at least ~ 5 decades of energy to those emitting radiation in the X-ray band (Waxman 2004b). Thus, if nuclei are accelerated with similar efficiency to a similar energy power spectrum, the fraction of energy deposited in $\sim 10^{18}$ eV CRs would be similar to that deposited by SNe in CRs accelerated to $\sim 10^9$ eV.

Let us next consider the constraint of Eq. (17) on the energy distribution within the ejecta. Consider a TRSN with a total kinetic energy of $E_{ej} = 10^{52}E_{ej,52}$ erg, an ejecta mass $M_{ej} = 10M_{ej,1}M_\odot$ and an energy E_r in a mildly relativistic, $\beta \geq 0.8$, part of the ejecta. Using Eq. (15), the ratio of the maximum energies of particles accelerated by the relativistic part of the ejecta, $\varepsilon_{max,r}$, and by the bulk of the ejecta, $\varepsilon_{max,ej}$, is

$$\varepsilon_{max,r}/\varepsilon_{max,ej} \approx 10^3 E_{ej,52}^{-1} M_{ej,1}, \qquad (19)$$

and the constraint of Eq. (17) is satisfied in the energy range of 10^{15} eV $- 10^{19}$ eV as long as

$$E_r > 10^{49} \frac{E_{ej,52}^2}{M_{ej,1}} \frac{\tau_c(\varepsilon_{max,r})}{\tau_c(\varepsilon_{max,ej})} \text{ erg}. \qquad (20)$$

Assuming that $\tau_c \propto \varepsilon^\delta$ we have

$$E_r > 10^{49} \frac{E_{ej,52}^{2-\delta}}{M_{ej,1}^{1-\delta}} 10^{3\delta} \text{ erg}. \qquad (21)$$

An upper limit to the value of δ in the relevant energy range, 10^{15} eV $- 10^{19}$ eV, may be obtained as follows. First note that the confinement time of $Z = 10$ particles at $\varepsilon = 10^9 Z$ eV is $10^{7.5}$ yr while and at $\varepsilon = 10^{17} Z$ eV it is larger than $10^{4.5}$ yr, implying that the average value of δ between these energies satisfies

$$\bar{\delta} \equiv \frac{\log(\varepsilon_h/\varepsilon_l)}{\log[\tau_c(\varepsilon_h)/\tau_c(\varepsilon_l)]} \leq 0.4 \,.$$

In fact, the value of δ in the energy range of 10^{15} eV $- 10^{19}$ eV must be lower than this average. The grammage (column density) traversed by CRs of energy < 1 TeV before they escape our Galaxy is $\Sigma_{conf} \approx 9(E/10Z \text{ GeV})^{-\delta}$ g cm^{-2} with $\delta \approx 0.6$ (Engelmann et al. 1990; Stephens & Streitmatter 1998; Webber et al. 2003), suggesting $\tau_c \propto 10^{7.5}(E/Z \text{ GeV})^{-0.6}$ yr for $E/Z < 10^{12}$ eV. As the value of δ at energies $10^9 Z$ eV $- 10^{12} Z$ eV is higher than the average, $\bar{\delta} \leq 0.4$, the value of δ must be lower at energies $10^{13} Z$ eV $- 10^{17} Z$ eV. It is reasonable to assume therefore $10^{3\delta} < 10$, which implies that the constraint of Eq. (21) may be satisfied for reasonable values of the parameters.

Finally, we note that Milgrom & Usov (1996) have suggested that cosmological GRBs, which occur in our galaxy once every $\sim 10^5$ years, could be the sources of the CRs in the energy range of 10^{14} eV to 10^{19} eV. This suggestion is quite distinct from the one presented in this article. While Milgrom & Usov (1996) considered acceleration by the highly relativistic jets of cosmological GRBs, where $\sim 10^{51}$ erg is carried by a highly relativistic, $\gamma \sim 10^{2.5}$ ejecta, we consider acceleration by mildly relativistic, $\gamma\beta \sim 1$, less energetic, $\sim 10^{49.5}$ erg, and more frequent TRSN explosions.

4. DISCUSSION

We derived constraints that must be satisfied by the sources of $\sim 10^{15}$ to $\sim 10^{18}$ eV cosmic rays, under the assumption that the sources are Galactic and that the CRs in this energy range are confined by the Galactic magnetic field (as explained in § 2.1, the CRs in this energy range are likely to be confined by the Galactic magnetic field since their Larmor radius is much smaller than the CR disk thickness). In § 2.1 we have shown that the Galactic occurrence rate, $\dot{N}_s$, of sources producing $\sim 10^{18}$ eV CRs and their energy production E_s per event must satisfy the constraints given by Eqs. (7) and (8) [E_s is the energy available for the acceleration of 10^{18} eV CRs, rather than the total event energy, as explained preceding eq. (1)]. In particular, E_s must be considerably lower than the kinetic energy of a typical SNe, $E_s < 0.03\dot{N}_{SN,-2}\zeta^{-1}E_{SN}$, where $\dot{N}_{SN} = 0.01\dot{N}_{SN,-2}$ yr^{-1} is the Galactic SNe rate. ζ in these equations is the ratio of the fraction of E_s deposited in 10^{18} eV CRs to the fraction of the kinetic SN energy that is deposited in $\sim 10^9$ eV CRs. These constraints must be satisfied by any candidate Galactic source. In § 2.2 and § 2.3 we derived additional constraints that are applicable to SNe and TRSNe. These sources are expected to accelerate particles to high energies through the collisionless shocks that they drive into the plasma surrounding the exploding star. In § 2.2 we derived constraints on the velocity of the shells ejected by the explosions [eqs. (13) & (15)], and in § 2.3 we derived constraints on the structure of the ejecta [eqs. (17) & (18)].

In § 3.1 we have shown that ordinary SNe are unlikely to be the sources of $\sim 10^{18}$ eV CRs, since they are unlikely to be able to accelerate particles to such energy and if they could, they would produce fluxes far exceeding the observed flux at these energies. We have furthermore shown that assuming that the flux of $\sim 10^{18}$ eV CRs is produced by the fastest part of the ejecta of SNe, which carry a small fraction of the ejecta energy, would predict a CR flux at lower energy, $\sim 10^{15}$ eV, which far exceeds the observed flux.

In § 3.2 we have shown that Galactic TRSNe may be the sources of high energy, $\sim 10^{18}$ eV, CRs. The mildly relativistic shocks driven by such ejecta are likely to be able to accelerate particles to energies exceeding 10^{18} eV. The estimated rates of TRSNe combined with the typical energy they deposit in mildly relativistic ejecta yield a flux of 10^{18} eV CRs which is comparable to the observed flux (under the assumption that the efficiency of the acceleration of particles in these shocks is similar to that of SNe and that the accelerated particle spectrum is close to $dN/d\varepsilon \propto \varepsilon^{-2}$, which, as explained in § 3.2 is supported by radio and X-ray observations). The large fraction, $\geq 10^{-2}$, of the kinetic energy deposited by such explosions in mildly relativistic ejecta ensures that if TRSNe are responsible for producing the observed flux at 10^{18} eV they do not overproduce lower energy CRs. Furthermore, since the TRSNe are a subset of the larger SNe population, their CR production is expected to smoothly join the lower energy CRs produced by SNe.

mological sources of high energy CRs (Wang et al. 2007). In the present work we have focused on Galactic sources.

REFERENCES

Aloy, M. A., Müller, E., Ibáñez, J. M., Martí, J. M., & MacFadyen, A. 2000, ApJ, 531, L119
Axford, W. I. 1994, ApJS, 90, 937
Blandford, R., & Eichler, D. 1987, Phys. Rep., 154, 1
Bamba, A., Yamazaki, R., Ueno, M., & Koyama, K. 2003, ApJ, 589, 827
Bell, A. R., & Lucek, S. G. 2001, MNRAS, 321, 433
Campana, S. et al. 2006, Nature 442, 1008
Cappellaro, E., Evans, R., & Turatto, M. 1999, A&A, 351, 459
Engelmann, J. J., Ferrando, P., Soutoul, A., Goret, P., & Juliusson, E. 1990, A&A, 233, 96
Gaisser, T. K., et al. 1993, Phys. Rev. D, 47, 1919
Galama, T. J., et al. 1998, Nature, 395, 670
Guetta, D., & Della Valle, M. 2007, ApJ, 657, L73
Hjorth, J., et al. 2003, Nature, 423, 847
Kulkarni, S. R., et al. 2000, American Institute of Physics Conference Series, 522, 191
Li, Z., & Waxman, E. 2006, ApJ, 651, 328
Liang, E., Zhang, B., Virgili, F., & Dai, Z. G. 2006, arXiv:astro-ph/0605200
Maeda, K., Mazzali, P. A., & Nomoto, K. 2006, ApJ, 645, 1331
Matzner, C. D., & McKee, C. F. 1999, ApJ, 510, 379
Mazzali, P. A., et al. 2006, ApJ, 645, 1323
Mazzali, P. A., et al. 2006b, Nature, 442, 1018
Milgrom, M., & Usov, V. 1996, Astroparticle Physics, 4, 365
Nagano, M., & Watson, A. A. 2000, Reviews of Modern Physics, 72, 689
Pian, E., et al. 2006, Nature, 442, 1011
Podsiadlowski, P., Mazzali, P. A., Nomoto, K., Lazzati, D., & Cappellaro, E. 2004, ApJ, 607, L17

Soderberg, A. M., et al. 2006, Nature, 442, 1014
Stanek, K. Z., et al. 2003, ApJ, 591, L17
Stephens, S. A., & Streitmatter, R. E. 1998, ApJ, 505, 266
Tagliaferri, G., et al. 2004, Bulletin of the American Astronomical Society, 36, 1207
Tan, J. C., Matzner, C. D., & McKee, C. F. 2001, ApJ, 551, 946
Vink, J. & Laming, J. M. 2003, ApJ, 584, 758
Völk, H. J., Berezhko, E. G., & Ksenofontov, L. T. 2005, A&A, 433, 229
Wang, X.-Y, Razzaque, S., Mészáros, P. & Dai, Z.-G, arXive:0705.0027
Waxman, E. 2004a, ApJ, 602, 886
Waxman, E. 2004b, ApJ, 605, L97
Waxman, E. 2004c, Proc. PASCOS 2003, Pramana 62, 483 (arXive:astro-ph/0310079)
Waxman, E. 2006, Plasma Physics and Controlled Fusion, 48, 137
Waxman, E., & Loeb, A. 1999, ApJ, 515, 721
Waxman, E., Meszaros, P., & Campana, S. 2007, Ap. J. in press (arXiv:astro-ph/0702450)
Webber, W. R., & Soutoul, A. 1998, ApJ, 506, 335
Webber, W. R., McDonald, F. B., & Lukasiak, A. 2003, ApJ, 599, 582
Woosley, S. E., Eastman, R. G., Weaver, T. A., & Pinto, P. A. 1994, ApJ, 429, 300
Yanasak, N. E., et al. 2001, ApJ, 563, 768
Zhang, W., Woosley, S. E., & MacFadyen, A. I. 2003, ApJ, 586, 356